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INTEGRATED ELECTROMECHANICAL DEVICES FOR ACTIVE CONTROL OF VIBRATION AND SOUND

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ABSTRACT

Advances in transducers and electronics have made possible integrated electromechanical devices for active vibration and noise control. This paper describes one such system which makes use of piezoelectric materials. An integrated device employing piezoceramic actuators and sensors, analog electronic signal conditioning, programmable control components, and a voltage amplifier is described. Issues driving design of each functional subsystem are addressed. The device is packaged using flex circuit technology and other electronics industry methods. The means of integrating transducers and other components are noted. Test results indicating the vibration suppression capability are presented, and the considerably greater possibilities for more sophisticated control designs using the same system are summarized. Potential applications in active vibration and sound control are described, and uses of the broader technology, beyond the specific device design, are summarized.

INTRODUCTION

The use of adaptive or smart materials in practical systems presents challenges which are often overlooked in basic research. Among the most important is the approach to integrating the materials with the other components necessary to produce a part, device or structure which performs required functions in a predictable and repeatable manner. This paper describes technology for combining one class of smart material, piezoelectrics, with electronic components to create devices for active control of vibration and sound.

There are numerous applications in precision systems where even a small level of vibration or vibration-induced sound is unacceptable. In the past, these vibrations were often reduced by redesign or possibly by passive damping and isolation techniques. Active vibration control is an alternative solution that can yield

increased performance with greater versatility. But active vibration control systems are usually heavier, bulkier, and more expensive.

Piezoelectric transducers are one of the most common means of producing and measuring vibration and sound. The paper describes why piezoelectric actuators and sensors are especially well-suited to integration with passive and active electronic components to form active vibration control devices. The particular concentration is on piezoelectrics used in thin wafer form for controlling bending vibrations and waves in structures. Results are provided from a programmable modular device built and tested specifically to demonstrate the technology.

Piezoelectric transducers have enjoyed widespread use over the last decade for vibration control in university, corporate, and government research laboratories, but introduction into applications has been slow. Why? First, the number of separate components -- actuators, sensors, signal conditioning, controllers, and power amplifiers -- required for a complete vibration control system has been large. Second, active piezoelectric vibration suppression has not been cost effective for most commercial applications. Finally, there is a legitimate lack of instances which may be cited as successful application examples. This work attempts to address the first concern while beginning to address the others. As basic smart structures research continues, a near term possibility exists for discrete electroactive material-based vibration suppression components like the one shown in Figure 1 as add-ons to traditional structures.

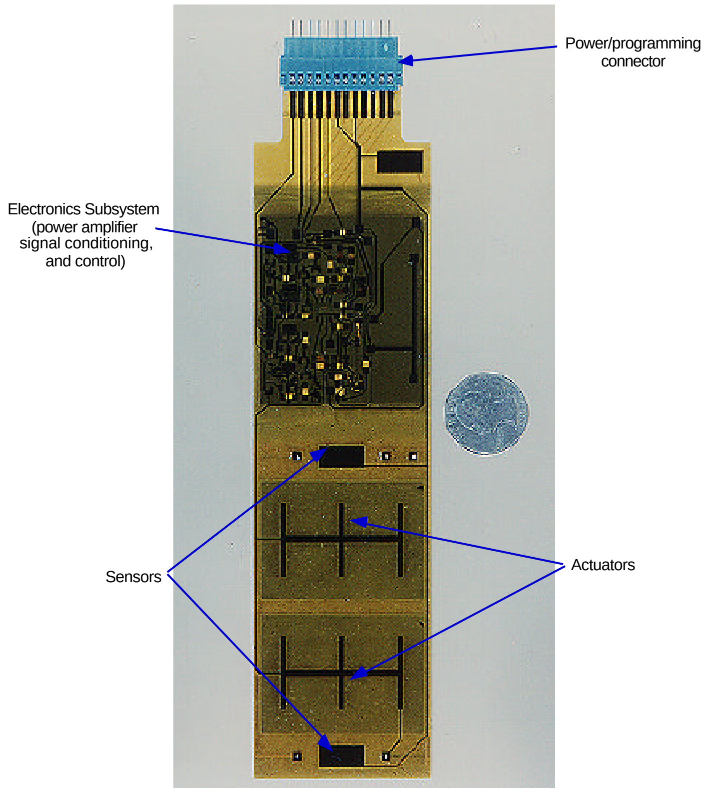

Figure 1: Top view of piezoelectric device

The paper begins by motivating the development of integrated active vibration suppression devices. It continues by outlining the roles of the various subsystems - actuation, sensing, signal processing (including control), and power conditioning - in the integrated system. The first two functions are performed by piezoelectric materials; the remaining trio is accomplished with an electronic subsystem. Actuation determines much of the geometry of the overall device, and it in turn dictates many of the properties of the other subsystems. The specific tradeoffs considered and their resolutions for each subsystem are detailed. Packaging technology used to layout and produce the device is described. The electronics industry packaging approach is transferable to other devices incorporating modified transducing or electronics subsystems. The paper concludes by summarizing the practical advantages of the technology as well as the open issues for improved integration, manufacturability, and performance. It describes how this technology can be incorporated into larger systems and suggests the types of economies of scale which would be realized with large scale production.

Passive Suppression Devices as Functional Models

Passive devices serve as functional models for their active counterparts, with the understanding that replication of passive functionality is only a starting point. Figure 2 shows schematics of two common passive systems used for vibration suppression. The first is a tuned mass damper (TMD) (den Hartog, 1934). This device type can be attached to structures to add significant damping to a single mode or, in some cases, to additional modes close in frequency. There are numerous ways to realize physically the simple mass-spring-dashpot system. The second passive system is a constrained layer viscoelastic treatment (Nashif and Jones, 1985). It consists of a relatively thin layer of lossy viscoelastic material coated by a much stiffer constraining layer. This distributed damping scheme is effective for vibration suppression over a somewhat broader frequency range.

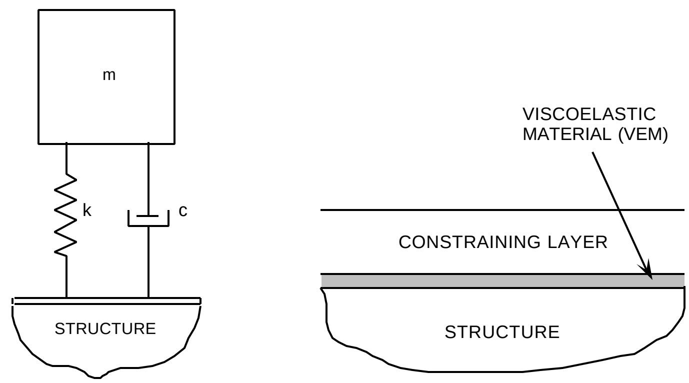

Figure 2: Modular passive damping systems with functionality desirable in an active piezoelectric device (left: tuned mass damper right: constrained-layer viscoelastic treatment)

Passive piezoelectric devices can be made to perform the same functions (Forward, 1979 and Design News, 1996). An active piezoelectric device capable of substituting for either or both of these passive systems while offering additional design freedom would be valuable for vibration suppression. With the proper control algorithm, either the single-mode damping of the TMD or the broadband damping of the viscoelastic treatment can be realized. The active damping performance has been achieved by numerous researchers using piezoelectric materials and laboratory supporting components and equipment, or occasionally using more compact supporting systems. However, these combinations of components and devices are too costly, bulky, and impractical for most applications.

Active vibration suppression devices will not enter widespread use if they function as nothing more than direct passive substitutes. Their additional cost must be justified by such features as programmability or adaptability. If it is done properly, integration of the components of an active system into a single unit can reduce cost while retaining additional functionality. Another benefit of an active system is the possible coordination of multiple devices to achieve a global objective.

Integrated Piezoelectric Devices

The present development is at the same time a culmination of work begun more than a decade ago in development of “smart” or “intelligent” structures incorporating piezoelectric actuators, and a starting point for more advanced electromechanical integrated devices.

The early smart structures work envisioned piezoelectric actuators and sensors combined with electronic components embedded in composite materials to create structures with artificial muscles, nerves, and brains. Other parallel developments have aimed at similar devices over the last several years (Bronowicki 1994, and Nye 1995). In a series of projects, that work has produced piezoelectric transducer devices and inserted them into research systems on the ground (Bronowicki, 1993) and in space (Nye 1995a and Blaurock, 1995). That effort took a different, approach to transducer packaging, using structural composite materials as a host into which the transducers were integrated. The present device uses flex circuit and other technologies to achieve similar goals. In the previous work, electronic support systems, with a relatively high-capability digital signal processor included, were integrated in a standalone compact package called the Modular Control Patch (Bronowicki, 1996). The current devices incorporate less local processing power, and distribute it with the transducers. External controllers are used in cases where global objectives beyond active damping are to be achieved.

Motivating Applications

The original motivation for the development of the integrated piezoelectric device was jitter reduction on spacecraft. The original space applications included:

- *Spacecraft Solar Array Yokes*. Solar arrays are one of the relatively few sources of vibration on-board most spacecraft. In particular, the array drive motors or quasi-static thermal inputs initiate vibration of the arrays, resulting in application of forces to the rest of the spacecraft bus at frequencies corresponding to the natural modes of the arrays. Passive or active damping of these modes can reduce significantly the level of transmitted vibration.
- *Spacecraft Booms*. Solar arrays are not the only appendages cantilevered from spacecraft busses. Other long structures are deployed or extended to support instruments, antennas, and sensors. Vibration of these booms can adversely affect other sensors on the booms or on the bus.
- *Instrument Jitter Reduction*. Individual instruments of sufficient size on board spacecraft have vibration modes which can be excited; the resulting jitter can lead to compromised sensor performance.

While there remain several specialized vibration reduction problems on spacecraft, the greater use of this technology is expected to take place on the ground. Other applications are reviewed at the end of the paper.

Device-Level Integration

The device-level integration employed is in contrast to other finer scales of integration. Larger structures such as aircraft skins might be created in the future using blended smart materials as a building block. Piezoelectric composites in which the piezoelectric component is distinguishable from the other constituents only on a very small scale are one example. However, the focus here is a device, not a material.

A useful term for describing the degree of integration in the present system is "mesoscale." Mesoscale integration implies combination of functionality and components on an intermediate scale which stops short of the microscales usually associated with MEMS, or smart composites. In the context used here, mesoscale refers to discrete electromechanical components and devices rather than micromachined systems or blended materials and composites. Typical physical dimensions of constituents are measured in millimeters or centimeters and the overall device size is measured in centimeters.

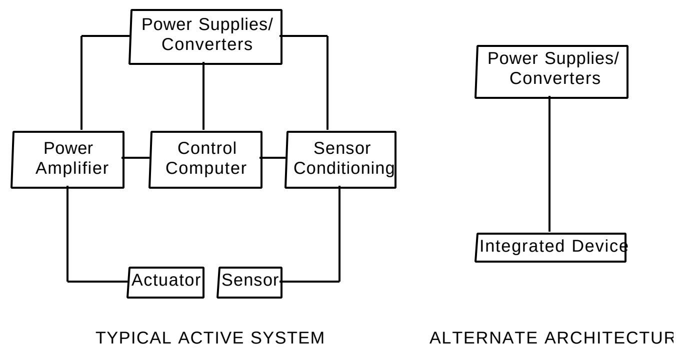

Figure 3: A simplified active vibration control system could integrate separate components into a single device

Smart materials introduce solid state means of transduction, provide a smooth energy transfer. Within the class of smart materials, piezoelectrics are uniquely suited for integration in a single electromechanical device. In contrast to other "smart" means of actuation and sensing, piezoelectrics act directly as linear transformers of electromechanical energy. They produce and measure stress and strain.

Piezoelectrics are used today in specialized applications. Figure 3 compares the typical piezoelectric-based active system using separate components with a more fully integrated system. The discrete-component system which might be found in a research laboratory, includes a separate actuator and sensor, laboratory-grade charge amplifiers, a control computer (a digital computer or analog circuits), and a combination power supply/amplifier. Its modularity allows the active system to be reconfigured for different experiments. However, the individual components are probably underutilized for targeted vibration suppression applications. In contrast, the right side of Figure 3 depicts the integrated system, which has considerably less total mass and volume. It still requires a power source, typically access to a DC bus. Reduced volume is achieved through elimination of duplicate and unnecessary hardware. For example, sensor conditioning, control, and power electronics all require power in the several Volt range. The same power bus can serve each subsystem. Additional channels and features of each separate unit are removed. Actuation and sensing share the same package, which also houses other components. The integrated system is likely to be less versatile than the laboratory collection, but will meet requirements for a wide class of vibration suppression applications.

The particular type of piezoelectric device suggested by Figure 3 is a low-profile system called a "patch" which can be bonded to the surface of a structure or embedded within a non-metallic structure. Physical integration of such a device can also take advantage of simplified manufacturing methods, and subsequently reduced fabrication costs. This is particularly true if standardized electronics

industry techniques for printed circuits and component integration are adopted. The piezoelectric transducers are the only nonstandard components which must be incorporated into the device.

Summary of Requirements and Design Goals

Requirements were established for the new device, including performance, system interfaces, and environmental compatibility. Environmental compatibility was considered in the contexts of space flight, clean room applications, industrial uses, and embeddability in composite or plastic structures. Specific requirements included:

- Achieve damping of $\zeta = 5\text{-}10\%$ for a single mode
- Effective over frequency range from 10 Hz to at least 200 Hz
- Achieve performance for structures at least as stiff as one-quarter inch thick aluminum
- Addressable by a digital computer and up to 10 parameters adjustable.
- Performance robust to typical changes in transducer and electronic component properties
- Device failure should not result in the introduction of any electrically-induced strain to the structure and should be easily determined by means of a simple check or test
- Quiescent power less than 20% of peak power
- Minimize ambient noise generation broadband and narrowband
- Standard temperature (-25C--55C) with possible extended operation
- Must operate in a vacuum and in non-volatile fluids
- Minimize heat generation, EMI, and outgassing
- Baseline for application to flat surfaces but allow possible use on shallow curved surfaces
- Actuation material would be capable of 200 microstrain of elongation. (With a 50 mm actuator width and a 0.5 mm actuator height, this corresponds to approximately 300 N force.)
- No local modes below 500 Hz in frequency when device attached to or otherwise integrated with a structure.
- Minimize total device mass.
- Provide indication to user of operational condition and limited diagnostic information as a check on correct operation.

Device Architecture

Fundamentally, the device transforms electrical power to influence mechanical systems. In order to accomplish this, there must be electromechanical coupling (the transducing subsystem) and electrical action (the electronic subsystem). The functional subsystems were packaged to meet overall requirements and other constraints while using processes suitable for low cost larger scale production. Packaging attempted to maximize efficiency.

One means of evaluating the spatial efficiency of a patch-type device is to express the area devoted to actuation as a fraction of the total device area. If available area is at a premium, any area allocated to non-actuation purposes might be considered wasted. A low overall height is also preferred. For applications involving structural embedment, the volume fraction and thickness fraction devoted to actuation are better figures of merit. The decision on overall architecture incorporated these concerns as well as questions relating to external interfacing and modularity of the device. Figure 4 summarizes six of the physical layouts considered for the patch and its transducing and electronic subsystems. Layouts 2, 4, and 6 include soft layers to protect electronics from shock and vibration. The electronics section can be stacked on top of the transducer section (5 and 6) reducing substantially the parasitic non-actuation area. Connectors are a practical issue for any real-world device, as are manufacturing issues. The final device used layout 1, an architecture well-suited to initial development. Future versions could employ one of the other architectures as necessary.

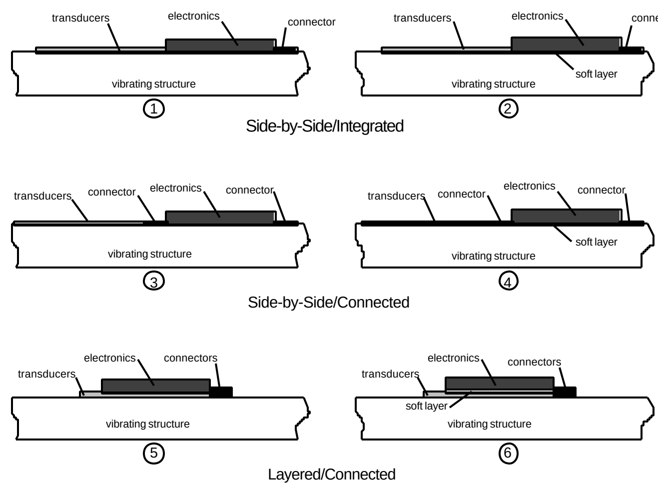

Figure 4: Options for layout of electromechanical transducing and electronic subsystems. Patches are shown bonded to the surface of a vibrating structure

Within the architecture of layout 1, there were several evolutions of the device. Table 2 summarizes the introduction of features during the patch development.

Table 2: Features added during each phase of the device development

Phase 0	Phase A	Phase B	Phase C
Piezo actuator encapsulated in polyimid	One of two piezo layers used for sensing Sensor charge amp package built into device	Low-voltage multilayer actuator Separate sensor piezoceramics Power amp added to elec. package	Add control components to elec. package Electronics compacted to reduce volume

Five Functional Subsystems

This section covers design of each subsystem. Actuation and Sensing are the two transducing functions. Signal Conditioning, Control, and Power Amplification are electronic functions.

Actuation

For vibration suppression applications, the actuator is perhaps the most critical element. The relative stiffness and total volume of the piezoelectric actuator determine the device authority over the vibrating structure. All other components of the active system should be designed to take full advantage of the actuation authority, an authority that can be compromised by substandard material properties, an underpowered amplifier, or a poor actuator-structure mechanical interface.

Because of access constraints, a practical piezoelectric vibration suppression device should be attached to only one side of a vibrating structure. The relative stiffness of the actuator and underlying structure can be calculated for simple systems, and explicit expressions for the induced curvature can be derived (Fuller, 1996). In more complicated structures, such as stiffened plates, the underlying stiffness is more difficult to calculate.

Since the actuator theoretically acts on the structure at all points directly beneath it, a larger area actuator allows the possibility of greater energy transfer, with the caveat that the wavelength of modes of interest should be larger than the actuator dimensions. The necessary actuator thickness is set by the underlying structure's stiffness and the level of ambient vibration to be suppressed. Inefficiencies are introduced if the actuator length and width are not large compared to its thickness. A single actuator with length and width in the low tens of millimeters is usually well suited to influence and damp modes with wavelengths in the range of tens of millimeters to hundreds of millimeters.

The actuator can be a single piece monolithic construction or be built up from multiple layers through the thickness, with individual layers wired in parallel. This approach has the advantage of requiring lower voltages for the same amount of actuation. However, if the material between the layers is compliant, actuation authority may be reduced. One promising avenue is the development of semi-monolithic multilayer actuators, fabricated with procedures used in producing the more common stack actuators (Ritter, 1995).

Other desirable actuator properties include:

- *High energy density*. This property expresses the structural energy capacity of a material. A soft material which is capable of large strain has lower energy density than a stiff material with the same strain capacity.
- *Simple electrical interface*. An actuator requiring extraordinarily high voltage or a complex amplifier is not desirable.
- *Predictable response characteristics*. Linearity over a wide range of inputs is preferred. Insensitivity to environmental inputs during fabrication or operation is also important.
- *Minimal heat generation.* An actuator integrated in an electromechanical device could generate sufficient internal heat to affect other components, or alter its own electromechanical performance.
- *Low cost.* Viability as a commercial product requires this.

Materials. The actuator material governs the electromechanical energy conversion efficiency. Limited consideration was given to non-piezoceramic materials such as lead magnesium niobate (PMN). PMN has been used successfully in stack type actuators for micropositioning and other applications. Strain capacity and energy density are approximately the same as those properties for piezoceramics, while dielectric hysteresis is lower, reducing self-heating concerns. Among the disadvantages of PMN are the quadratic nonlinear electromechanical response, greater temperature sensitivity of material properties, higher permittivity and capacitance, and lack of heritage in fabrication of wafer type forms. Other piezoelectric forms such as polymer films have lower energy density and are unable to survive moderately high fabrication or operational heat inputs.

Lead zirconate titanate (PZT) piezoceramic is the most common transducing material, and several compositions are available. The basic decision in selecting PZT actuation materials comes down to “hard” versus “soft” compositions, e.g. PZT-4 and PZT-5. Harder materials have slightly higher energy densities, lower piezoelectric d coefficients, and higher coercive fields. Thus, for a larger applied voltage across a given thickness, the PZT-4 compositions can produce as large a strain as the PZT-5 compositions generate at a lower voltage. In addition, the harder materials are less likely to age and are less subject to stress-depoling. The special interest in this development in very low voltage operation directed effort away from the harder compositions despite their benefits. For fabrication reasons, PZT-5A was a good compromise. However, the design and integration approaches allow use of any PZT composition.

Multilayer Actuation. Multilayer actuators (MLAs) can provide the same amount of displacement and force capability as monolithic piezoceramics using less voltage and more current. For example, instead of a single 10-mil layer of PZT, a MLA uses four 2.5-mil layers. While the single layer might be operated at up to 200V, the four-layer system could produce the same response with 50V applied. The MLA approach was pursued in Phase B of the effort, with fabrication of a 28 V device.

The experimental MLA fabricated for this project included 13 layers of PZT, each 38 microns thick. Individual electrodes within the stacked actuator were connected along one actuator edge. Each MLA was treated as a single monolithic wafer for purposes of design and integration with flex circuit components. The internal electrodes were terminated to a wrap around to conductive layers on the side connected to either the top or bottom surface conductor.

In the longer term, MLAs are promising, but several concerns arose during the development:

- *Electrode cost* For very thin PZT layers, the electrodes take up more of the total volume of the actuator and drive the cost.
- *Actuator size.* It is difficult to make larger multilayer actuators. 1 x 1 inch is a comfortable size, with warping not perceived to be a problem. Larger actuation areas in a patch would have to be synthesized using multiple MLAs.
- *Actuator thickness.* To reduce warping effects, 20 mils is close to the minimum feasible total thickness.
- *Layer thickness.* The minimum thickness is dictated by warping and wear-through during flattening operations. Note that too thin a layer is not desirable if the interlayer electrode thicknesses cannot be reduced correspondingly.
- *Reliability.* The three-dimensional stress fields within the layers and the novelty of the processing steps make this an issue.

Several key MLA equations are noted for reference. The electric field applied to the each of the N layers of a MLA is

$$E_3 = \frac{V_3}{t_{layer}} = \frac{NV_3}{t_a} \qquad (1)$$

where V_3 is the voltage, t_a the total actuator thickness, t_{layer} the layer thickness, and electrode thickness is ignored. The applied electric field must be below the coercive field. A value of 800 V/mm (20 V/mil) is a conservative limit suitable for bipolar drive and operation. The voltage required to reach this field is

$$V_3 = E_3 t_{layer} = \frac{E_3 t_a}{N} \qquad (2)$$

Using a larger number of layers to make up a given actuator thickness reduces the voltage requirement. Table 1 gives values for maximum voltage required to achieve the maximum field assuming various layer thicknesses.

Table 1: Maximum voltages for different actuation layer thicknesses (assumes 800 V/mm max. field)

Layer Thickness		Max. Bipolar
microns	mils	Voltage (V)
250	10	200
200	8	160
150	6	120
100	4	80
50	2	40
38	1.5	30

The capacitance of the layered actuator is

$$C^T = \frac{N^2 e^T A_a}{t_a} \qquad (3)$$

where A_a is the wafer area, and $\varepsilon^T = \kappa^T \varepsilon_0$, indicating a capacitance proportional to the square of the number of layers. The current requirement, considering the actuator as a capacitor only, is

$$I_3 = wC^T V_3 = wNe^T A_a E_3 \qquad (4)$$

The current demanded increases with frequency, the dielectric constant of the material, the size of the patch, the applied field, and the number of layers.

Voltage-strain hysteresis curves for one MLA specimen are shown in Figure 5. The maximum voltage shown is 18 V peak. The important features of these data are the slopes and widths of the curves. They are very similar to what would be expected from a monolithic piece of PZT-5A. The percentage hysteresis increases with strain amplitude. Tests of five MLAs showed an effective d_{31} coefficient of 239 pm/V at 4.5 V input, 266 pm/V at 9.1 V input, and 321 pm/V at 18.2 V input. An actuation subsystem using two MLAs was incorporated into the Phase B prototype patch.

Interdigital/Interdigitated Electrodes. Another possible means of achieving larger actuation forces in low-profile piezoelectric transducers is to use interdigitated (or interdigital) electrodes. This technique could apply equally well to single-layer or multilayer actuators. Interdigitated electrode concepts have been implemented successfully in a number of systems (Cutchen, et al., 1975 and Shimizu, et al., 1983), and details of this approach are described elsewhere (Hagood, et al., 1993). The basic idea of interdigitated electrodes is to actuate the piezoelectric material more nearly along its poling direction. This can be achieved in a wafer by introducing an alternating electrode pattern. The piezoelectric material is poled using a high field applied to the electrodes. Subsequently, field applied using the same electrodes actuates the material in most regions according to the d_{33} piezoelectric coefficient. An improved actuation performance of two times or more is achievable theoretically. It is possible to implement this concept by screening the electrode pattern directly on the piezoceramic or by etching a pattern into a separate copper-Kapton material which is then bonded to or cured around the wafer. The use of interdigitated electrodes may be promising in the future. It was demonstrated in this development, but the high voltages required were less practical outside the laboratory.

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Figure 5: MLA actuator #39 Strain vs. voltage for 25 Hz sine wave

Actuators with interdigitated electrodes were fabricated and tested using 10-mil (250 micron) thick PZT-5A. Three different patterns of electrodes were etched on copper-Kapton sheets for testing of three different specimens. The 60-mil electrode spacing resulted in the largest strains, although the voltage level required to achieve the same field was 50% and 200% higher than in the 40-mil and 20-mil spacing cases. The effective value of the d coefficient is relatively high. for example, 400 microstrain at 800 V/mm field gives an equivalent d of 500 pm/V.

Final Subsystem. After successful demonstration of a novel thin multilayer system, the final (Phase C) prototype employed an actuation scheme made up of six separate piezoelectric wafers in three layers with each wafer having dimension 1.8 x 1.3 x 0.010 inches each. The layers are separated by copper-plastic material which serves as an electrode and a means of carrying current to and from the actuators.

Sensing

In contrast to actuation, sensing does not benefit greatly from large volumes of piezoelectric material. Though the charge generated by a piezoelectric sensor is proportional to its surface area, signal-to-noise difficulties are usually not encountered with even relatively small (e.g. 1 cm x 1 cm) sensors. The sensor performance is influenced by both electrical and mechanical aspects of the actuation. Poor circuit design or improper shielding may introduce electrical crosstalk. Mechanical interaction is more difficult to avoid. The bias was towards a strain sensor to achieve compatibility with the piezoelectric strain actuation. A planar piezoelectric strain sensor was selected. The sensor system produces a signal proportional to the sum of the two in-plane normal strains.

Three possible classes of wafer actuator/sensor configurations are summarized in Table 2. Configuration (a) places the transducers side-by-side on the surface of the structure. In configuration (b) the sensor is stacked directly above the actuator. In configuration (c) a single piezoelectric functions as both sensor and actuator. In any case, the overall size of the sensor should be the size of the actuator or smaller. The sensor length and width should be significantly greater than the thickness.

Table 2: Comparison of options for actuator-sensor integration

Issue	A: Side-by-side	B: Stacked	C: Single trans.
Use of surf. area	Inefficient	Efficient	Efficient
Collocation	Not perfect	Perfect	Perfect
Local strain	Possible problem	Signif. concern	Signif. concern
Other issues	Asymmetry	Shielding	Mismatched bridge

There are examples of all these configurations (Fanson and Caughey, 1990, Bronowicki, et al., 1994, Anderson and Hagood, 1994, and Vallone, 1995). The sensor-actuator design impacts the collocated sensor-to-actuator transfer function. Tight pole-zero spacing makes active damping ineffective. Anderson (1995) presents further details.

Other properties were considered desirable in the sensor.

- *Compatibility with actuation*. This implies a sensor which can be integrated well mechanically, is relatively immune from actuator-related EMI, is not strongly affected by local stress fields, and, with the actuation, results in a desirable collocated transfer function for control.
- *Low noise*. The primary requirement of the sensor is that it report information correctly. This requires a minimum of noise.
- *Predictable response characteristics*. As with the actuator, the sensor should provide an output directly proportional to the physical quantity of interest.
- *Low cost*. The sensor and conditioning must perform a simple task well. This is not an area which should require high cost.

A finite element model was developed to aid the sensor pair location decision. The model included a piezoceramic actuator surrounded by a softer plastic material on the surface of a beam. The model was run to determine how closely the sensors could be placed to the actuators and still avoid large local stresses induced by the actuation. Closer placement was desired to minimize the total size of the transducing subsystem.

All area actuators and sensors perform spatial averaging while they transduce. A model was developed to examine the filtering characteristics and the relative compatibility between the sensor and actuator. This indicated that the transducers are not capable of accurately sensing or actuating very short wavelength deformation. It is interesting to note that the two-sensor package surrounding the actuators prevents the collocated transfer function from becoming non-positive real until a shorter wavelength (higher frequency). This property is desirable for the types of control implemented in the device.

The sensor spatial characteristics were designed to match those of the actuation system. The charges from two independent piezoelectric ceramics on either side of the actuators were combined. Two 0.5 mm (20 mil) piezoceramic wafers were used as the sensors for the final device. These sensors have in-plane dimensions 0.25 x 0.5 inch and a capacitance of approximately 10--15 nF.

Sensor Signal Conditioning

Integration of sensor conditioning with the sensor itself has become common in temperature, pressure, and motion transducers. The Analog Devices ADXL accelerometer series is one well-known example. In general, placing conditioning close to the sensor reduces the effect of corrupting noise from various sources by boosting and filtering the transducer signal. In the case of piezoelectric sensors, a charge amplifier acts as the conditioner. The conditioning system may be sensitive to nearby power circuits in an integrated device. In the present device layout, the distance from sensors to signal conditioning was minimized. The conditioning is a straightforward variable-gain charge amplifier.

Control

The control subsystem is a direct extension of the signal conditioning, and in practice the two can share electronic components. A combination of analog and digital components may be used. Individual active and passive components may also be integrated into application specific integrated circuits (ASICs) and multichip modules (MCMs). The system developed by Bronowicki and Rohleen (1996) uses a MCM with a DSP for control. Depending on the specific control algorithm used, narrowband and broadband control schemes may require fundamentally different architectures or different arrangements of physical components. In any case, the control system should employ standard low-cost components, preferably those available in surface mount packages.

Algorithms. The control algorithms used were simple, effective, and reliable. Strain rate feedback (SRF) and positive position feedback (PPF) were the two control types implemented in the for the following reasons:

- SRF and positive PPF control laws are simple to design.
- Both algorithms can add damping to resonant structural modes.
- Both control laws are based on second-order filters, making them simple to implement using analog electronics.

- The performance of each is robust with respect to small changes in the resonant frequencies of the controlled structure.

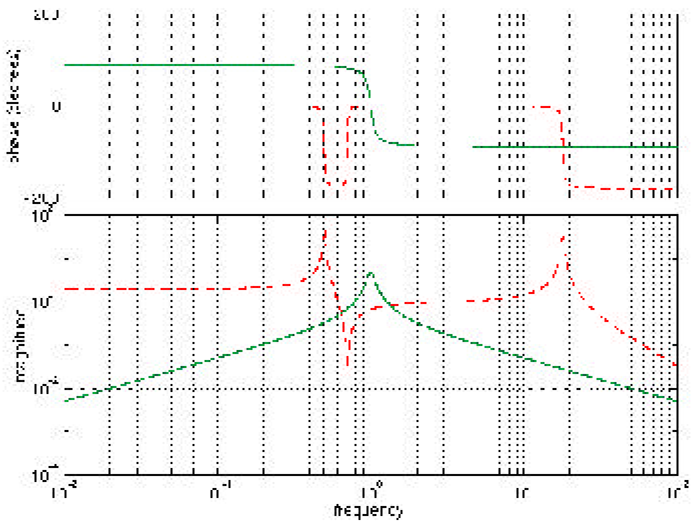

Figure 6: Example sensor-actuator transfer function (dashed) and an SRF compensator (solid)

SRF is a second-order control law of the form:

$$V_{act}(s) = \frac{g w_f s}{s^2 + 2 z_f w_f s + w_f^2} V_{sens}(s) \qquad (5)$$

$V_{sens}(s)$ is the sensor voltage as a function of the Laplace variable s and $V_{act}(s)$ is the voltage output to the piezoceramics. The control law is a function of the controller gain, g, the natural frequency of the filter, ω_f, and the nondimensional damping ratio, ζ_f.

Figure 6 shows a representative plant transfer function and the SRF compensator. The phase shift due to the SRF compensator above the controller pole causes the second resonance to be out of phase with the target mode (Figure 6). Therefore, the overall gain of the compensator is limited by the structural dynamics that occur above the target resonance.

Positive position feedback (PPF) is a control law of the form:

$$V_{act}(s) = \frac{g w_f^2}{s^2 + 2 z_f w_f s + w_f^2} V_{sens}(s) \qquad (6)$$

The three parameters for the PPF filter are the same as for the SRF compensator. The primary difference between the two compensators is that SRF rolls off with a slope of -20 dB/decade at frequencies above the resonance pole and PPF rolls off with a slope of -40 dB/decade. In Figure 7, the idealized plant transfer function is the same as in the SRF design example. The PPF compensator is usually designed such that the compensator pole is close in frequency to the resonance being controlled but has a relatively large amount of damping as compared to the target mode.

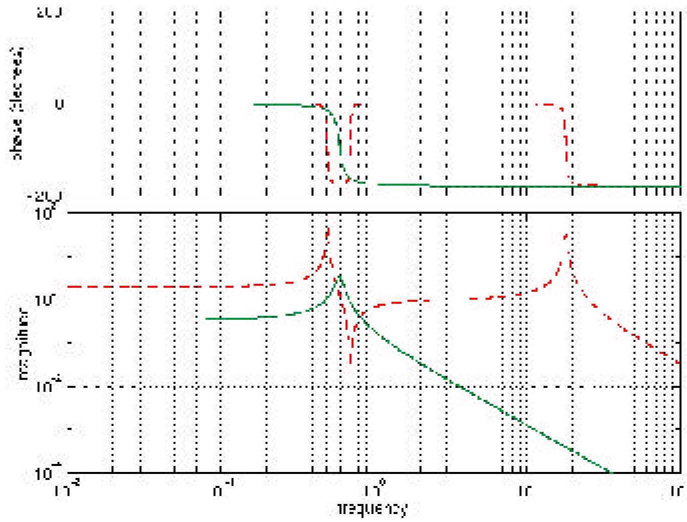

Figure 7: Example sensor-actuator transfer function (dashed) and a PPF compensator (solid)

Another difference between the loop gain for the PPF design and the loop gain for the SRF design is the frequency at which closed-loop stability is determined. The PPF compensator rolls off at a slope of -40 dB/decade, therefore the high frequency pole of the open-loop transfer function is gain stabilized. The closed-loop stability is determined by the low frequency loop gain, which is much closer to 1.

The active device was built with SRF and PPF controllers on-board. However, it is possible to override this local control or use it in combination with an external controller. The programmable package allows the user to combine SRF and PPF if desired to synthesize fourth-order controllers to suppress vibration. The use of other control algorithms of arbitrary complexity is possible if the user is willing to supply additional controller hardware. The device provides access to the unfiltered charge amplifier output as well as the low pass filter (PPF) output. An actuator input is also available. Within the electronics package, the external signal is combined with any generated by the on-board controllers before being sent to the actuator power amplifier. A creative user could use an external algorithm (broadband, adaptive, feedforward, etc.) while the local control continued to function.

Hardware. Several other properties or features were considered in the controller development. Three levels of autonomy were investigated:

•None/Fixed: The control law is hardwired and cannot be changed

•Person-in-the-loop: The control law can be changed through an external interface by a person

•Autonomous: The control system can sense its environment and change parameters without external intervention

The moderate complexity second option was selected.

The need to withstand power shutdowns and outages was considered critical. A means of storing non-volatile controller parameters within the device was required.

Three main options were considered for realizing the control: analog, digital, and hybrid. The hybrid digitally-programmable implementation was selected. Analog was incapable of easy adjustment but would be cost effective for specific applications. Microcontrollers (8-bit or 16-bit) could be included in a future version.

Power Amplification

The piezoelectric actuator is a capacitive load requiring current to be delivered at a specified voltage over a certain bandwidth. The size of the voltage needed to achieve a certain fraction of the material's coercive field depends on the actuator layer thickness. One possible benefit of using lower voltage actuation is the resultant ability to use lower cost, more standard power components. Many spacecraft have available a 28 VDC bus, and the initial goal was to design to this supply. The Phase B prototype operated from a 28 V bus. It is also possible to use DC-DC converters to achieve the desired rail voltage(s).

While the two signal-level electronic subsystems are relatively unobtrusive, there is a fundamental difficulty in integrating the power system with the other electronic components. Two issues arise. The first, and potentially the more difficult one, is the need to dissipate heat, which is generated even when the power system is in a quiescent state, not delivering current to the actuator. The heat generation increases significantly when large amplitude high frequency current is delivered, and the amount of current required increases with actuation area. The second issue relates to the amplifier type. If, in an attempt to reduce power consumption and total heat generation, a switching amplifier is selected, the resultant EMI becomes a concern. Both feedthrough to the other electronic components and potentially other environmental concerns may arise. Finally, operation from a unipolar supply requires a bridge amplifier. DC-DC conversion can be used within the package to increase supply voltage. Table 4 compares amplifier options. A discrete linear system was used in the devices.

Table 4: Comparison of 4 power amplifier options

	Integrated	Discrete
Linear	Compact, proven, concentrated heat source	Low-cost, greater volume, better heat distribution
Switcher (PWM)	Efficient, costly, concentrated heat source	Unproved, better heat distribution

Packaging and Fabrication

The fabrication technology matured considerably during the development. This section describes key motivation and design considerations.

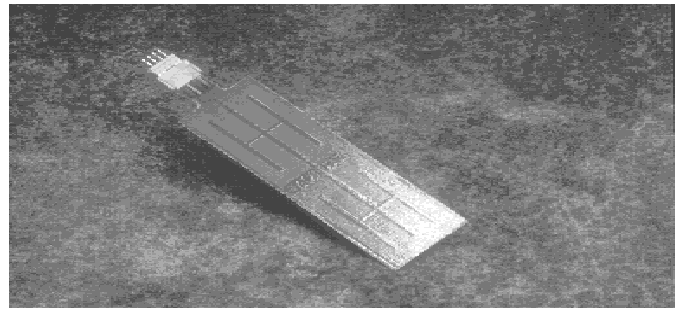

Figure 8: The QuickPack design was used as the basis for the device transducer package.

Background

The overall approach during this program was to build on a developing transducer packaging technology (Figure 8). A piezoceramic actuator encapsulated in a polyimid skin with copper traces offers a range of advantages to the raw piezoceramic actuator, and now, the added electronic components. These include:

- robust packaging of the brittle ceramics
- extending the life expectancy of the piezoceramics
- redundancy for connecting to the electrodes actuator
- a cost effective and high-volume-compatible connection method
- easy bonding to structure
- an electrically isolated package
- an environmentally robust actuator impervious to moisture, jet fuel, hydraulic oil and salt fog
- the ability to integrate electronic components together with the piezoceramic actuators to yield highly functional devices
- robust packaging of the electronic components to minimize solder failures

Figure 8 shows an existing package built around four 0.010 inch piezoceramic sheet actuators located at two stations. It includes a simple connector and a distinctive electrode pattern which provides redundant connection to the piezoceramic electrodes so that if the ceramic cracks, connection to the majority of the electrode surface will be made. Overall thickness is 0.039 inches. This packaging technology entails curing the piezoceramic actuators between two layers of copper traces and a polyimid skin. The polyimid skin is thin and durable, providing the electrical isolation and durability to the package without sacrificing the strain transfer of the actuators to the substrate to which it will be bonded.

The First Step: Phase A Prototype

In the Phase A package, the upper layer was used as a sensor. An area dedicated to sensor signal conditioning was added. This section of the package was mechanically isolated from the base structure by a thin layer of viscoelastic material. The intention was to prevent the electronic components from experiencing large mechanical stresses. Surface mount components were used in the conditioning, which was essentially a charge amplifier.

Resistive elements were incorporated into flex circuits. Modifications to the existing actuator package were made. Conductive inks and solder pastes, and performance and reliability of the components were evaluated. The solder interconnect survivability, power dissipation, and ability of components to withstand strain levels were assessed. Op amp dies were also integrated separately onto customized flex circuits. The patches were instrumented with three additional foil strain gages each. Basic functionality was checked. The gain adjustment for the sensor signal was also verified, although the miniature surface mount potentiometer was crude to use.

Packaging Electronic Components

The packaging technology is based on layers of polyimid, copper traces, spacer material and epoxy. These layers are laid up and then cured together. The standard actuator patch includes two layers of piezoceramic actuators, with a polyimid skin with copper traces on the outside and a layer of polyimid with additional copper traces between the two layers to make intermediate connections. This packaging method is very flexible, able to accommodate a range of geometries. Inspection points were designed into the manufacturing process. By integrating the electronic components with the polyimid skin and copper traces, the electronic module and the actuators and sensors can be combined into an easy-to- manufacture-package. A variety of packaging and process enhancements were required. These included:

- interconnection between the top and bottom layers of the package to close the electrical circuit
- installation of the passive components pad size and solder temperatures for compatibility with the package materials
- installation of the ceramic substrate resistors and capacitors such that they survive the cure process
- demonstration of the robustness of the solder connections to the high strain environment of the vibrating structure

These steps allowed for the extension to more complex devices such as ICs. Several IC packaging options were evaluated, including die form devices mounted to the circuit material and wire bonded to copper pads, leadless ceramic carriers, and surface mount plastic and ceramic packages. The packaging options needed to satisfy a host of criteria including:

- robust to vibration environment of installed package
- low profile
- ability to withstand curing process
- robust to handling on circuit before final cure
- high yield on installation with the circuit material
- compatible with requisite thermal management
- compatible with various vendor processes should high volume supply be required
- availability and cost of the devices in the packaging options that were selected

It was determined that surface mounted devices were most appropriate. These included ICs, transistors, digitally programmable devices and thermally resettable fuses.

Flexibility In Packaging

A potting process for the electronic components evolved over the course of the development. Initially, the tooling required for a given electronic layout was highly customized to assure uniform potting with minimal air pockets, and smooth top and bottom surfaces. After a few iterations, a modified potting methodology which required more universal tooling was developed, allowing for more flexibility in the design process, and ultimately lower costs for slightly customized designs. For Phase B, the packaging process was able to accommodate the unlapped surfaces of the multilayer actuators as well as the soft silver electrode material.

Once the electronic component package type was selected, it remained to determine how to ensure as compact and dense an electronics module as possible while using discrete ICs. A two-layer construction was used. Making use of the interconnects evaluated as part of the passive component installations, and ensuring that there was insulating material between the two layers. Potting materials were chosen to ensure adequate electrical isolation between the layers. Strict rules regarding trace widths as well as spacings were used to ensure as dense of a layout as possible within the constraints of the circuit material. The overall height of the package was not uniform over its length. The piezoceramic actuators were substantially thinner than the electronic components, and it was not desirable to stiffen the actuator region with additional. As a result, the package had two distinct thicknesses, as well as transition regions as the package changed from one height to the other. The final dimensions of the package were 18cm $\times$ 5 cm $\times$ 0.32 cm. The ratio of transducer area to electronics area was 1.7:1.

Fabrication

The device included six piezoceramic actuators, three piezoceramic sensors, a host of electronic components and a convenient connector. The integration step included building up the package layers including the polyimid skins with copper traces and components, the piezoceramics, the spacer material and epoxy and the top polyimid skin with additional electronic components. Note that at intermediate points in the process inspections were made. All packages were tested for functionality, and actuator and sensor capacitance. The cure process was closely monitored to ensure that the epoxy flow was complete.

Peripheral Components and Programming

A power/programming interface was developed for the final device. It provided +/-48V, +/-15V and routed the communication from a PC. Four female D15 connectors on a back panel connected the patches, and a D25 connector provided access to and from the PC parallel port.

The software was required to allow the user to set the following parameters

- Option to override local control
- Type of local control (PPF/lowpass or SRF)
- Filter frequency, ω_f
- Filter damping or Q
- Control gain, g

The user interface was designed to be straightforward. The implementation of particular control parameters is “black box” from the user's standpoint. A DOS C program was written to interact with the programmable components on board the device. Filter parameters, external input control and on-off capability can all be controlled using this program. The program utilizes the parallel port of a PC or its equivalent. Three wires are used. Interaction with the patch includes reading, writing, and transfer of information within the devices. Each device includes eight adjustable settings and four 8-bit, nonvolatile memory locations. This gives capability to store four different settings while actually implementing a fifth set. The PC is not required once programming is complete.

Test Results

Thermal Tests on Phase B Prototypes

A series of tests was performed on the Phase B patches to determine the thermal characteristics for typical operating conditions. Temperatures were measured at 8 locations for quiescent operation and sinusoidal drive. Each type of test was performed with three different thermal boundary conditions on the patch. Main results were:

- The bottom (trace side) of the patch heated up more quickly, got hotter due to quiescent power dissipation, and had a higher temperature rise per milliamp of supply current than the top side of the patch.
- Insulating only one side of the patch increased quiescent heating and temperature rise per unit of supply current approximately 10--20% as compared to the uninsulated case.
- Insulating both sides of the patch increased the temperature rise by a factor of two or three compared to the uninsulated case and increased thermal time constants from approximately 3 minutes to between 6 and 10 minutes.
- Current draw as a function of frequency depends on the drive amplitude and not the thermal boundary conditions.
- Temperature rise as a function of supply current was relatively insensitive to drive amplitude but strongly dependent on the thermal boundary conditions.

These tests highlighted the difficulty in increasing the amplifier bandwidth beyond 300 Hz while maintaining thermal stability under typical operating conditions. The inter-component spacing was reconsidered in light of the results.

Phase C Thermal Impedance Design

To meet the operating temperature requirements, it was necessary for the packaging system to allow sufficient cooling such that the temperature of the electronic components did not exceed their specified range and to physically separate heat sources. Typical operating temperature ranges for the individual electronic components are up to 150 C. The average power expected to be delivered to the actuators was 3.4 W. This power was being delivered in a push pull configuration such that individually the amplifiers were each providing one half the power and hence at a potential operating temperature of 55 C. The thermal impedance of the package was required to be less than 56 C/W. Tests estimated the thermal impedance of the package to be 35 C/W.

Life/Longevity Tests

Longevity tests were conducted to verify durability of the components, interconnects, and overall packaging. The Phase B patch bonded to a stiff hexagonal platform to measure the fidelity of the power amplifier and actuation system over a large number of cycles. The device was driven with a 10 V peak 100 Hz sine wave input. DC current draw from the +28 V supply was monitored (84 mA was a nominal value). Other quantities of interest included the patch strain output, the output from the separate strain sensor, and the temperature of the upper patch surface at each of four hot spots above heat-dissipating components. The test was halted after one billion cycles had been accumulated with no degradations noted.

Vibration Suppression Tests - Phase B

Cantilevered beams served as system test articles in all vibration suppression tests. The one-eighth inch thick aluminum beams were 2x15 inches. One of the patches was bonded to a cantilevered beam specimen and tested in a component tester, with a non-contacting shaker used to input a force at the tip. An accelerometer was substituted for the Eddy current displacement sensor. The ability to implement different control strategies was verified.

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Figure 9: Tip force to tip acceleration transfer function using Phase B prototype with PPF control on mode 1

Figure 9 shows the improved damping in the first mode with PPF. Figure 10 shows the increased damping in the second mode with PPF. Performance with SRF was, as expected, less impressive. It is difficult to damp lower frequency modes significantly without destabilizing higher frequency ones. The results demonstrated that the control characteristics could be adjusted remotely.

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Figure 10: Tip force to tip acceleration transfer function using Phase B prototype with PPF control on mode 2

Vibration Tests - Final Prototype (Phase C)

The programmability of the final prototypes was tested with the devices on a benchtop. Transfer functions from the unfiltered sensor output to the output of the low pass filter were recorded to verify performance and ability to change gain, *Q*, and frequency. Figure 11 shows the filter response for *Q*=2 and a frequency near 10 Hz. Figure 12 illustrates the capability to change both *Q* and the low-pass filter frequency (10, 20, 30, and 40 Hz). The gain is 1.0 in all cases. Figure 13 shows a typical result from a closed loop laboratory test. The plot indicates that a measured frequency response on a beam-like test structure can be modified by the inclusion of the patch device. In this case, the goal was to add damping to the first mode of the structure.

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Figure 11: Low pass filtered output for three values of gain

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Figure 12: Low pass filtered output for four programmed frequencies and values of *Q*

In Figure 13 the PPF controller parameters were 15 Hz, *Q*=1.5, gain of 382. The open loop first mode at 16.0 Hz with damping ratio 1.9% was shifted to 14.2 Hz with a damping ratio of 24% in the closed loop. In Figure 14, the PPF controller parameters were 234 Hz, *Q*=3.0, gain of 200. The open loop second mode at 232 Hz with damping ratio 0.7% was shifted to 235 Hz with a damping ratio of 5.1% in the closed loop. The first mode was shifted down to 15.1 Hz and damping increased slightly, to 2.3%.

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Figure 13: Collocated transfer function shows damping of mode 1 with PPF control - open loop (solid) and closed loop (dashed)

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Figure 14: Collocated transfer function shows damping of mode 2 with PPF control - open loop (solid) and closed loop (dashed)

Figure 15 shows a typical use of the device. A laptop PC is employed to tune the patch parameters for a machine vibration suppression application.

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Figure 15: User programming of SmartPatch control system parameters for a machine vibration application

Projected Applications

This section summarizes possible applications.

Government and Aerospace Uses

- *Spacecraft Solar Array Yokes and Booms*. Although the array application was not focused on as heavily as expected, it retains some relevance. The usefulness of the technology on booms depends on the boom geometry. It may be difficult to retrofit patches onto these structures if there are no areas to locate them.
- *Spacecraft Component Vibration Reduction*. Passive systems are used frequently to suppress vibration during launch. The source of power must be addressed before this application is feasible.
- *Acoustic Control of Payload Fairings*. One approach to reducing acoustic inputs on satellites during launch is to control the motion of the intervening fairing structure. The feasibility of this approach is still being investigated, but an integrated piezoelectric device could play an important part in overall noise and vibration suppression.
- *Missiles*. In order to hit the airborne target, the seeker stage and supporting components must be relatively free from jitter. Damping can reduce this jitter, and programmable active damping is tailored easily to different systems.
- *Airborne Laser (ABL).* At this point, there is not a specific ABL use in mind. However, there are numerous vibration and noise concerns with the planned system.
- *Aircraft Noise Control.* Active noise control is being researched and implemented for helicopters and propeller-driven aircraft. The SmartPatch may have use because it has achieved a level of integration which exceeds other available options.
- *National Ignition Facility*. This DoE effort includes vibration-sensitive optical components which could benefit from suppression.
- *Aircraft Racks and Shelves*. Passive damping is presently employed to reduced fatigue-causing vibration within various military aircraft. An active solution is now viable in some cases.
- *Aeroelastic Control*. Tail buffet is a concern in twin-tail aircraft. The ongoing effort using piezo actuators could add electronics as a next step. (Lazarus and Saarma, 1995)

Other Projected Uses

- *Research.* University and other researchers in smart structures, active noise/vibration control, etc. have expressed strong interest in purchasing small numbers of SmartPatch devices. The integrated nature of the device will enable this group to concentrate on issues other than soldering to piezoelectrics, building power amplifiers, and wiring up controllers.
- *Damping of Vibrations in Machines.* Passive vibration suppression solutions are often applied to machine vibration problems. With the availability of an integrated active damping device, an alternative approach is now possible. Many of these machines include flat surfaces which will accept the SmartPatch well.
- *Precision Machining*. There are numerous applications for active damping in industrial machines. Reducing jitter is important for improved finish and throughput.
- *Semiconductor Manufacturing Equipment.* This industry is perhaps most demanding of a vibration-free environment. There are needs in the manufacturing, test, and inspection areas.
- *Active Noise Control.* Two groups of applications are possible: source cancellation and acoustic enclosures. Examples of the former class include transformers, compressors, and other machines typically housed in sheet metal enclosures. Acoustic enclosures surround sensitive components or equipment to keep sound out. Passive systems can be heavy and are not effective at low frequencies.

- *Optical Benches*. One of the systems of interest in space and terrestrial applications is a bench-type structure, a relatively stiff plate-like construction designed to maintain position of components while minimizing relative motion.
- *Home Appliances*. This area requires both noise and vibration suppression. Yet the panel-type structures in air conditioners, washing machines, dishwashers, and refrigerators are good candidates for damping. Power is readily available. In this class of large volume applications, it is likely that an active device could be tailored to streamline components and reduce parts and production costs. Eventually, a more hardwired version, possibly using strictly analog control components, might be needed to stay within cost constraints.
- *Automotive Applications.* The most important point about this market is the extreme cost-competitiveness. Active vibration and noise control will only be feasible if costs are low. The present device and its low-cost components are a first step in this direction.

Conclusion

This paper has summarized development of a piezoelectric-based electromechanical device useful for suppression of vibration and noise. The device is representative of a broader technology which combines piezoelectric transducers and electronic components in efficient, low cost packaging. The motivation and requirements for the specific device were elaborated. Each of five functional subsystems - actuation, sensing, sensor conditioning, control, and power amplification -- was discussed. The devices constructed used available piezoceramic wafers for actuators and sensors, but prototype devices were constructed using novel low-voltage multilayer actuators and actuators with interdigital electrodes. Packaging considerations were discussed. Test results indicating the vibration suppression performance and device programmability were presented. The devices are one example of an integration technology which can be adapted to a variety of applications.

Acknowledgments

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